

REGIONAL EVENT IDENTIFICATION RESEARCH IN ASIA

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ABSTRACT

Recent event identification efforts at Los Alamos National Laboratory (LANL) have focused on mining event ground-truth data collection in central Asia and testing far-local to near-regional discriminants using earthquakes, mining explosions, and single-charge chemical explosions. Our mining event efforts have identified over 20 mines and more than 1,000 mining explosions from around the former Soviet nuclear test site (KTS) in eastern Kazakhstan. Using the Kazakh National Data Centre (KNDC) bulletin from 2002 to 2007 and waveforms recorded at station KURK and array MKAR, we combined time-of-day seismic-event analysis, waveform cross correlations, seismic-event location methods, and image analysis to identify active mines. From our previous, but more limited studies, we had assumed mining explosions in eastern Kazakhstan occur only between about 8 AM and 8 PM local time. However, our latest study, using several thousand events, reveals that some mines shoot near midnight local time. Thus, we concluded that only during the hours of 21, 22, and 23 GMT (3, 4, and 5 AM local time) can we assume that the small events from this region are probable earthquakes.

Using this assumption, we selected 8 events within about 250 km of station KURK as earthquakes, and we selected about 250 mining explosions from three mines for discrimination analyses. In addition, we gathered all available depth-of-burial (DOB), hole-closing, and tunnel-closing single-charge chemical explosions that occurred at KTS from 1997 to 2000 and were recorded at KURK. The single-charge chemical events occurred within about 125 km of KURK. From published reports, we have flagged three of these events as fully contained. For the mining events, we do not know the shooting practices, such as delayed-firing along rows of shotholes.

Using the events described above, we tested spectral-ratio and phase-ratio body-wave amplitude discriminants. We find that contained, and even most partially contained single-charge explosions can be separated from earthquakes using a high-frequency ($F > 4$ Hz) Pg/Lg ratio. For some mines, events do separate from the earthquakes at $F > 4$, but for other mines, Pg/Lg ratios must be formed at $F > 7$ before separation from earthquakes occurs. We also processed the mining events to detect spectral banding related to delay-fired shooting practices. Our cepstral analysis indicates that events from some mines have more pronounced spectral modulations than events from other mines.

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OBJECTIVES

Over the past year we have continued studies to collect mining-event ground-truth data in central Asia, focusing on a portion of eastern Kazakhstan surrounding the former Soviet nuclear test site (KTS). We have also collected waveforms from single-charge chemical explosions detonated at KTS in the late 1990s, and we have identified a few small earthquakes based on time-of-day analysis. We have therefore assembled seismograms of uncontained mining explosions, both contained and uncontained single-charge chemical explosions, and earthquakes. We have used these event types to test discriminants that can separate mining events both from earthquakes and from single-charge explosions at far-local to near-regional distances.

RESEARCH ACCOMPLISHED

Kazakh Mining Ground-truth Study

We have been expanding our seismic ground-truth data collection efforts for central Asia by identifying mines and mining explosions. Working with Kazakh National Data Centre (KNDC) bulletins (2002–2007), we combine time-of-day seismic-event analysis, waveform cross correlations, seismic-event location methods, image analysis, and seismic discrimination methods to identify active mines in the area between the International Monitoring System (IMS) array MKAR and the Global Seismic Network (GSN) station KURK. Most of the events within this area occur during daytime (Figure 1), are usually small (often recorded at only 1 or 2 stations or arrays), and therefore tend to be poorly located. Our goal is to tie event clusters to specific mine sites, and thereby establish ground-truth location and event type (earthquake or explosion) information.

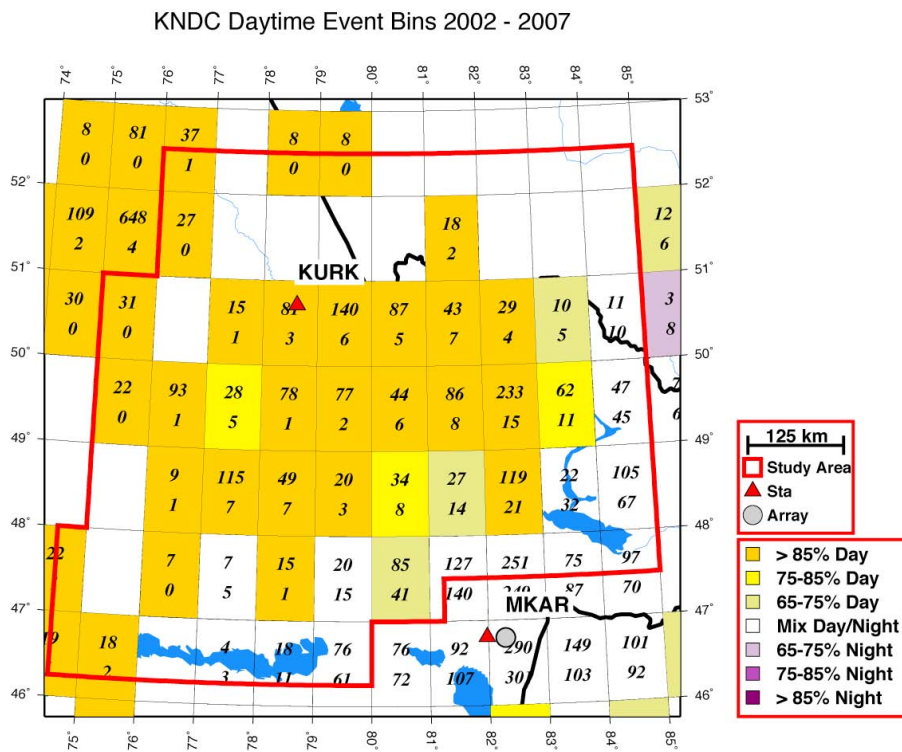


Figure 1. Time-of-day seismicity for eastern Kazakhstan and surrounding regions. The primary event-information source is the KNDC web-published bulletin. Gold and yellow regions are dominated by daytime mining explosions. Within each bin, the upper number is the daytime event count and the lower number is the nighttime event count. We focused on the area within the red box between array MKAR and station KURK, which includes the former Soviet nuclear test site (KTS).

Using KNDC locations as a guide, we assembled about 2,500 three-component, event-segmented waveforms from MKAR array-element MK31. After bandpass filtering between 1.5 and 5.5 Hz, we cross-correlated the first 20 seconds of each component's event record with every other event record from the same component (that is, broadband frequency (BHZ) was correlated with other BHZ records, etc). After stacking and normalizing the individual component correlations into three-component correlations, we assembled similar-event clusters based on peak correlation coefficients exceeding 0.4. From the relative timing offsets within a given cluster's correlation peaks, we time-shifted, aligned, and stacked the individual event waveforms to create a single, three-component record at stations MK31 and KURK, and we stacked MKAR seismic hazard zone (SHZ) array elements. These waveform sums become the reference waves of each event cluster. Figure 2 shows the stacked BHZ wave and several aligned individual waves at station MK31 for event cluster 310 (see Figure 3 for event cluster locations).

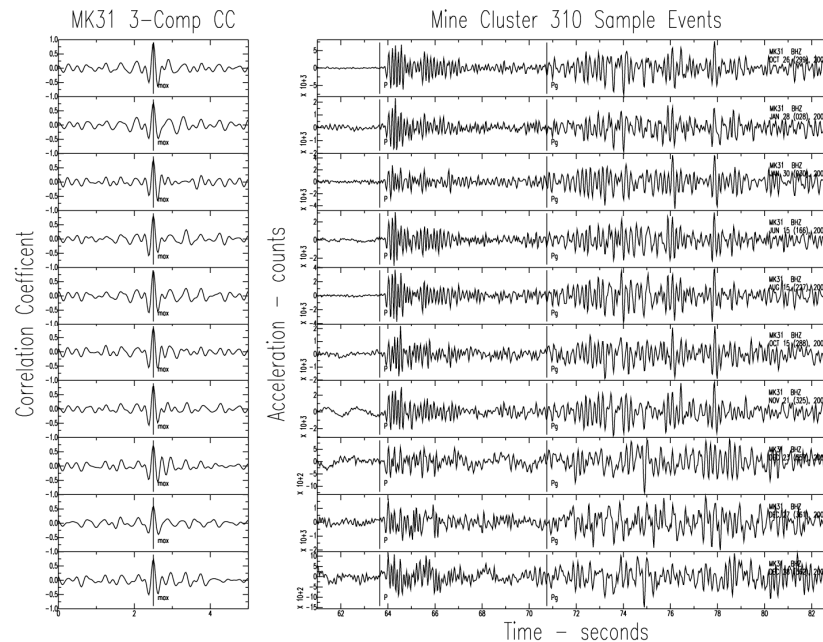


Figure 2. Event cluster 310 sample waveform stack (top trace) and individual, vertical-component, time-aligned P-waves at MK31. The three-component cross-correlation results are shown at left, with autocorrelation at top left. Note improved S/N ratio on the stacked wave for Pn (first break).

In all, we found 23 clusters, each with 5 or more events from probable mines, totaling for about 1,000 individual events. Event-station distances for the clusters are between about 75 and 550 km, and most event magnitudes are between about 1.0 and 3.5 mb (Figure 4). Although nearly all mining events occur during local daytime (about hour 2 GMT to hour 14 GMT, or 8 AM to 8 PM local time; Figure 4), we did find two clusters where events occur predominantly at night. Figure 5 contains a map and histograms from one of these event clusters. Events occur during probable work shift changes in the morning (2 GMT), in the evening (10 GMT), and at midnight (18 GMT). From previous studies (MacCarthy et al., 2008, Hartse et al., 2007) we had assumed unclustered, night events were earthquakes, but from our current study we have abandoned that assumption. For discrimination research, we now assume only events occurring during hours 21–23 GMT (3–5 AM local time) are earthquakes.

Final Ground-Truth Event Selection

Because we wanted to conduct discrimination studies involving the three event types—mining explosion, single-charge explosion, and earthquake—we selected data from station KURK. KURK has operated under the KZ and II network codes and has archived digital data available from the Incorporated Research Institutions for Seismology (IRIS) Data Management Center (DMC) going back to 1994. KURK therefore recorded nearly 20 single-charge chemical explosions from various locations around KTS, including (1) the 1997 DOB experiments (Glenn and Myers, 1997), (2) the Omega test series of tunnel explosions (Knowles, 2006), and (3) other hole-closing explosions (NNC RK, 1998).

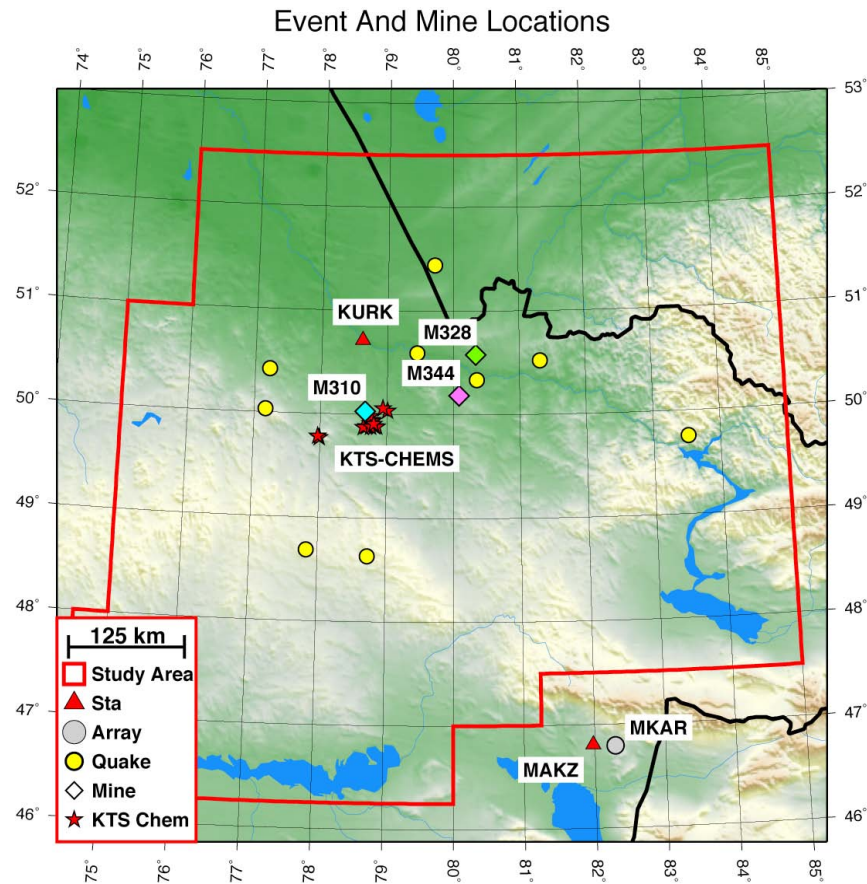


Figure 3. Study area showing approximate mine locations (diamonds), single-charge chemical explosions (stars), and probable earthquakes (yellow circles). We estimated that the mine locations and the earthquake locations are from the KNDC; the KTS explosions are from published reports. About 250 individual mining events are represented by the 3 mine locations.

KURK has also recorded many of the mining explosions, which we identified in our waveform similarity study as described above. Because of the low magnitudes of nearly all events in this area, for signal-to-noise purposes we limited the mining events to those occurring within local to near-regional distances of station KURK. We therefore selected about 250 events from three distinct mine clusters at distances of between about 100 and 150 km from the station (Figure 3).

Identifying ground-truth earthquakes around the relatively aseismic KTS is difficult. While there are plenty of seismic events, nearly all appear to be mining explosions. For the selection of earthquakes, we limited events to those within 250 km of KURK with origin times only from hours 21 to 23 GMT (see Figures 4 and 5). As described above, these were the only hours where we observed no waveform-clustered mining events. We also presumed any event within 350 km of KURK with m_b larger than 4.0 was also an earthquake, regardless of origin time. Figure 3 shows the locations of the 9 presumed earthquakes we selected.

Summarizing, our final discrimination data set includes about 250 mining explosions, 18 single-charge chemical explosions, and 9 earthquakes, with nearly all events within 250 km of KURK. Figure 6 shows sample vertical-component waveforms from each event type.

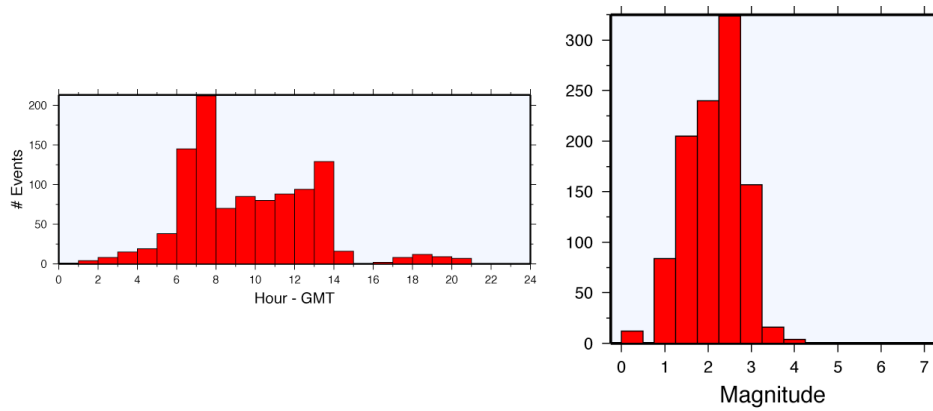


Figure 4. Summary time-of-day and event magnitude histograms for 23 mining event clusters around KTS. Local daytime (8 AM to 8 PM) runs from 2 to 14 GMT.

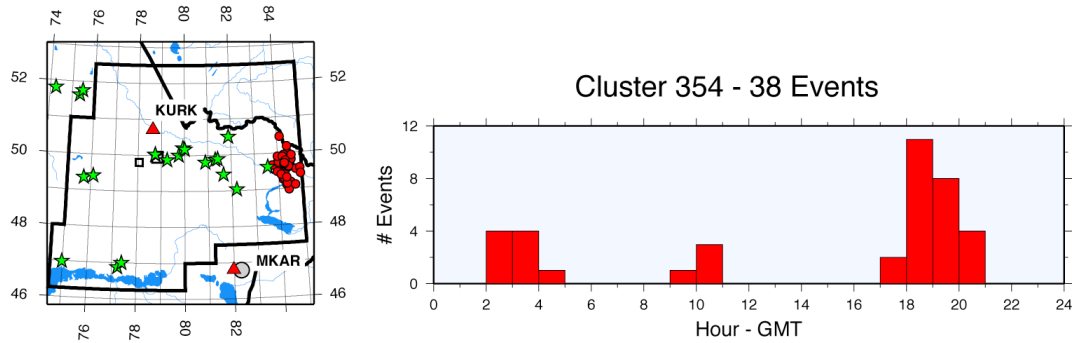


Figure 5. Time-of-day histogram and event map for mine cluster 354; an example of night mining explosions. The map shows KNDC locations as red circles. Reported mines are green stars. Note that most events occur from hours 18 to 20 GMT, with local midnight at hour 18 GMT.

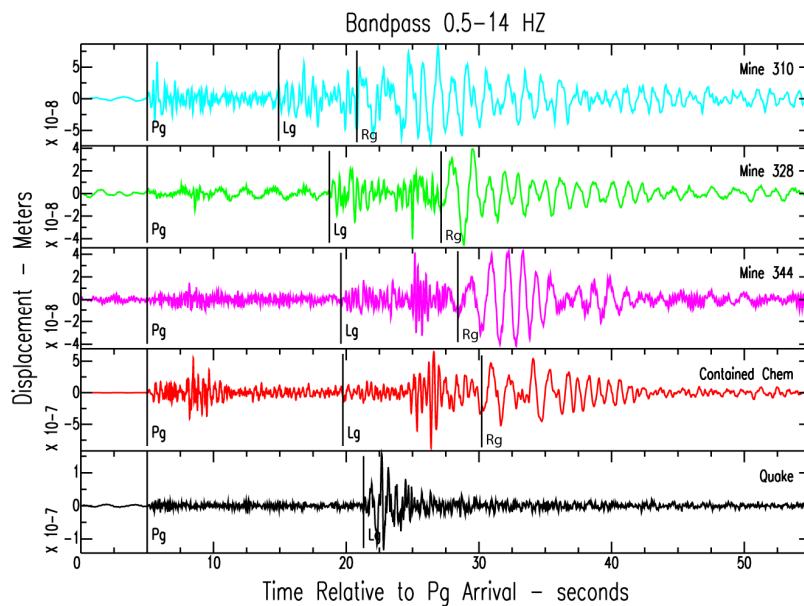


Figure 6. Sample waveforms from each of three mines; a KTS contained, single-charge explosion; and a probable earthquake. Note the lack of Rg on the earthquake.

Seismic Event Discrimination Results

Most events in our data set are within or only slightly beyond the crossover distance of KURK. Thus, we measured Pg and Lg body wave amplitudes [as root mean square (RMS) displacement in meters] and measured pre-phase and pre-event noise windows. Hartse et al. (1997) describes the measurement methods we followed. We formed Pg/Lg amplitude ratios and corrected the ratios for a distance trend prior to forming final ratio-versus-magnitude discrimination plots. We used only earthquake ratios to find the distance trends. We did not attempt any other corrections, as we currently hold only 9 earthquakes from the study area.

Figure 7 shows discrimination results from station KURK, comparing only the earthquakes and the KTS single-charge explosions. Most hole-closing and some tunnel explosions at KTS were shallow and not contained. We are confident that at least two DOB explosions were contained. These explosions vary in size from about 2 tons up to 100 tons. Only two uncontained explosions are within or near the earthquake population. The contained and the majority of the uncontained explosions separate from the earthquakes. Figure 7 demonstrates that small, single-charge explosions can be separated from earthquakes using a high-frequency P/S ratio at local to near-regional distances, even when containment is not complete.

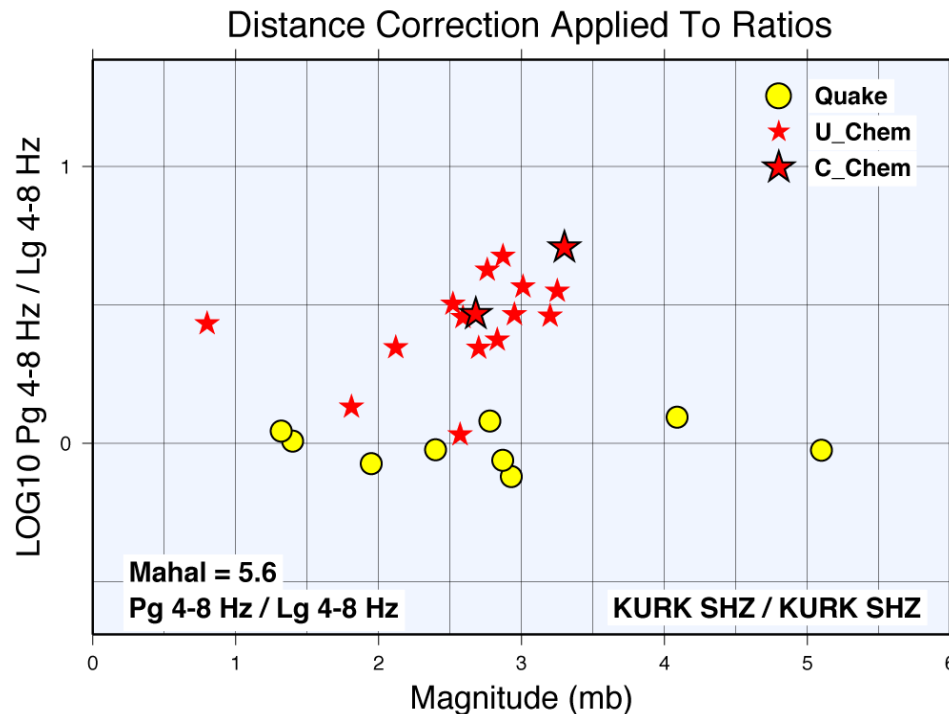


Figure 7. Pg(4–8 Hz)/Lg(4–8 Hz) ratio versus magnitude for single-charge chemical explosions and earthquakes. As expected, the contained—and most uncontained—explosions separate from the earthquakes.

Figure 8 uses the same ratios as Figure 7, but the events from the three mines are now included. We find that events from Mine 310 separate from the earthquakes, but the explosions from Mines 328 and 344 do not. This could be a function of the source-area geology, explosive emplacement depth, or shooting style. To test for evidence of multi-hole, delay-fired shooting, we applied the method of Arrowsmith et al. (2007) to derive a cepstral estimate for each earthquake and mining explosion (Figure 9). We obtained the cepstral results using the array elements at MKAR. The larger cepstral numbers indicate a greater probability of delayed shooting. At Mine 310 it therefore appears that delayed shooting is more common than at the other mines, but Mine 344 also has several events with larger cepstral numbers. On the discrimination ratio plots, we flag a mine explosion as “delayed” (diamonds with black borders) when the event cepstral number is above 10. Figure 8 shows that “delayed” shots at Mine 310 separate from earthquakes, but “delayed” shots from Mine 344 do not. We therefore conclude that delayed shooting by itself does not control the event separation seen on P/S ratio plots.

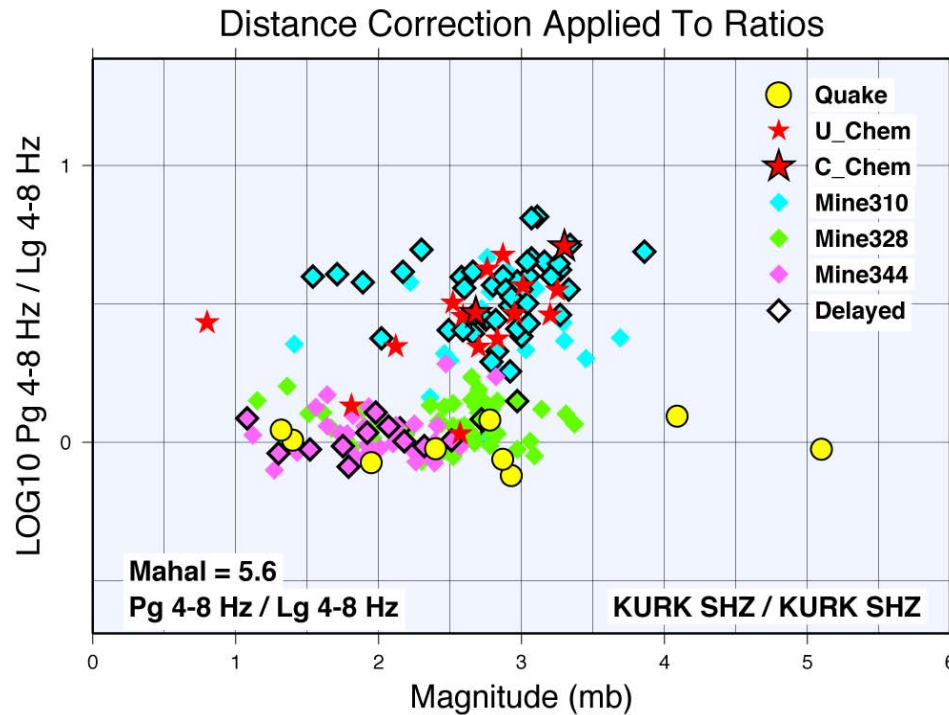


Figure 8. Pg(4–8 Hz)/Lg(4–8 Hz) ratio versus magnitude for all explosions and earthquakes. Events from Mine 310 separate from earthquakes, but events from other mines do not.

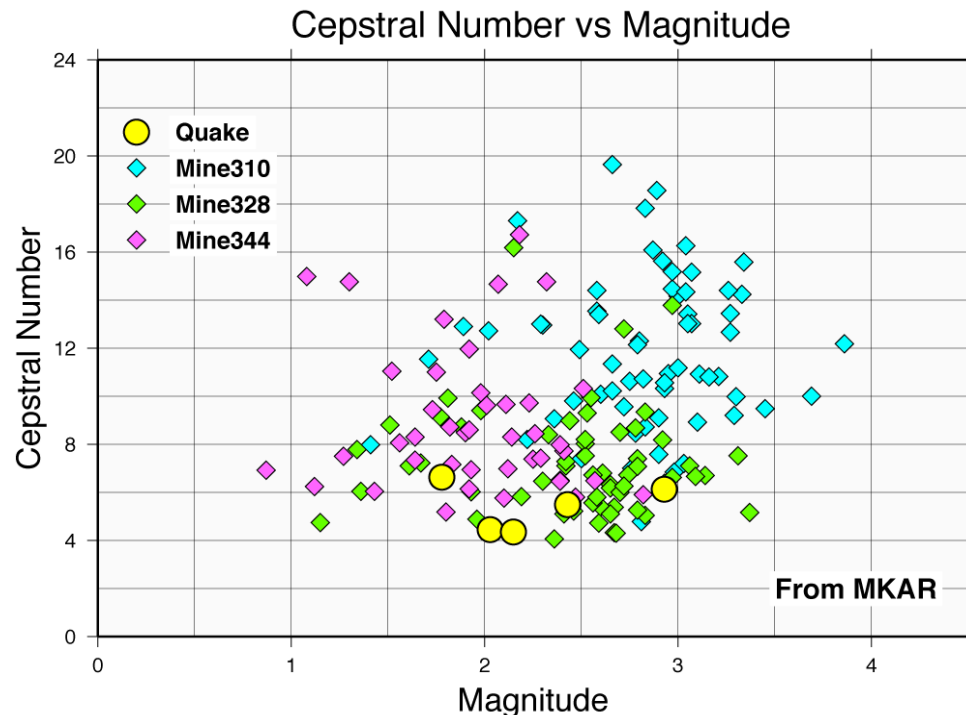


Figure 9. Cepstral number versus magnitude for earthquakes and mining events. Larger numbers indicate probable delay-firing shooting practices. Delay firing at Mine 310 appears to be a more common practice compared to the other mines.

Figure 10 shows that increasing the frequency band of the measured Pg and Lg amplitudes can improve separation of mining events from the earthquakes. For example, all events from Mine 344 are moved above the earthquake

population when the Pg/Lg ratio is formed at the 7–14 Hz band (compare Figures 8 and 10). The ratios from Mine 328 also begin to rise above the earthquake ratios. Because of the behavior of the anti-aliasing filters at KURK, the 40 samples per second data we used can only be measured to about 14 Hz, but these results suggest it may be possible to improve the separation of mining events from earthquakes by measuring appropriate data streams at even higher frequency bands.

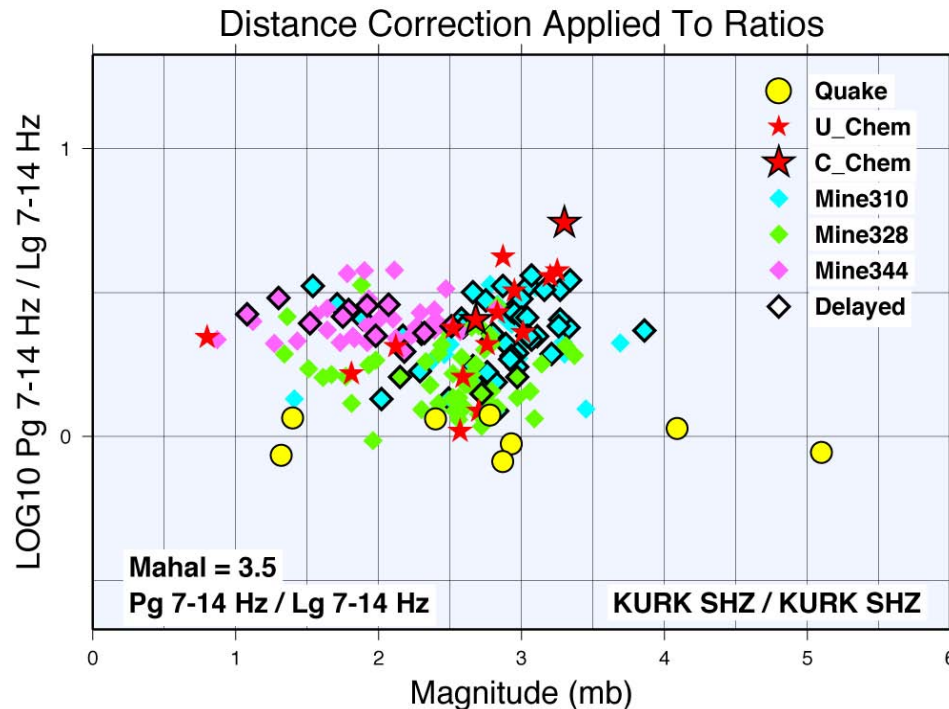


Figure 10. Pg(7–14 Hz)/Lg(7–14 Hz) ratio versus magnitude for all explosions and earthquakes. Events from Mine 344 now separate from earthquakes. Compare to Figure 8, where the band is 4–8 Hz.

The waveforms shown in Figure 6 show a strong Rg arrival for both mining and single-charge explosions relative to the direct Lg phase. This suggests that, within the appropriate group-velocity window, an Lg coda amplitude could be measured and placed into a ratio with direct Lg to form an earthquake-explosion discriminant. We determined that an Lg coda velocity window between 2.7 and 2.2 km/s captures the Rg arrival for these local to near-regional events, and we then measured RMS amplitudes in the 0.5–1.75 Hz band. The Lg/Lgcoda discrimination plot is shown in Figure 11. The “delayed” mining explosions have the same ratios as the mining explosions with small cepstral numbers. The earthquakes have no Rg, and true Lg coda was measured. Because most earthquakes were small and at distances greater than 200 km from KURK, only three had coda amplitudes that remained above background noise. But those three earthquakes are clearly separated from the explosions. One contained, single-charge explosion had a small direct-Lg amplitude and a large Rg arrival, resulting in separation from the mining events (lowest red star on Figure 11). The second contained, single-charge explosion and two other single-charge explosions are at the bottom of the mining event population. This suggests a possible discriminant for separating contained and uncontained explosions, but further information regarding the emplacement and containment of the single-charge events is necessary before conclusions can be reached.

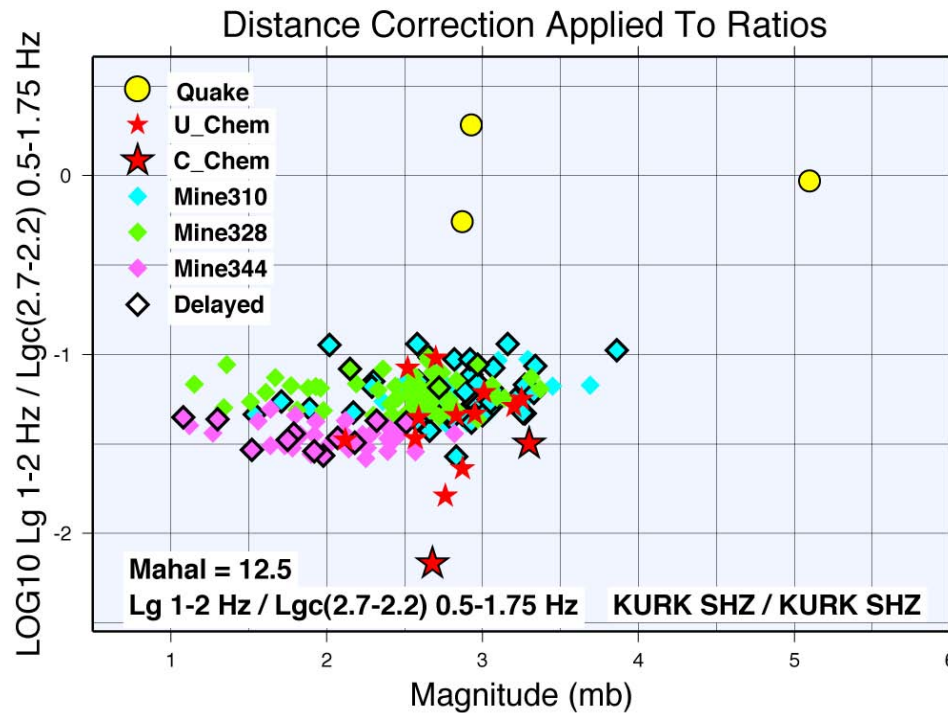


Figure 11. $\text{Lg}(1\text{--}2\text{ Hz})/\text{LgCoda}(0.75\text{--}1.75\text{ Hz})$ ratio versus magnitude for explosions and earthquakes. We measured the amplitude of the Lg coda over a velocity window between 2.7 and 2.2 km/s, which captured the Rg phase of the explosions (see Figure 6).

CONCLUSIONS AND RECOMMENDATIONS

We have an ongoing program to identify mining seismicity clusters and establish ground-truth mining event information from waveform correlations. For our eastern Kazakhstan study area, we have tied over 1,000 events to 23 distinct mining-event clusters. Event time-of-day analysis shows that mining explosions occur during all hours of the day in eastern Kazakhstan, except during the early morning hours (hours 21–23 GMT). We have identified 9 earthquakes near KTS and station KURK by assuming that early morning events are earthquakes. We have also assembled KURK waves from contained and uncontained single-charge chemical explosions detonated during experiments from the late 1990s at KTS. Using the earthquakes, single-charge explosions, and mining explosions from three mines near KURK and KTS, we have tested several discriminants. We find that (1) the high frequency (4–8 Hz) Pg/Lg ratio separates earthquakes from contained and even partially contained single-charge explosions, but this discriminant does not separate many mining explosions from the earthquakes; (2) increasing measurement frequency to above 7 Hz begins to separate mining explosions from earthquakes; (3) apparent delay-firing of mining events does not seem to influence the Pg/Lg discriminant performance; and (4) Lg/Lgcoda ratios that exploit the presence of the Rg phase may be useful for separating mining explosions from earthquakes and, possibly, contained explosions from uncontained explosions. We will continue to investigate discriminant measurement and correction methods in an attempt to improve performance in separating mining events from earthquakes and single-charge, contained explosions.

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